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WELDALITE ™ 049 (Al 2095-T8): ANISOTROPY EFFECTS AT CRYOGENIC CONDITIONS

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Tensile, fracture, and FCGR testing was performed on a plate of the aluminum-lithium alloy Weldalite™ 049 (Al 2095-T8) over a temperature range from ambient to liquid helium (4K) conditions. Properties were developed on specimens removed from various orientations within a 12.7 mm (1/2 in) nominal thick plate to characterize anisotropy with respect to strength and toughness. Strength and FCGR properties are compared to the conventional aluminum alloy 2219-T87, developed for similar cryogenic applications.

Results indicate a high degree of anisotropy with respect to strength and ductility, with the lowest strength/highest ductility occurring at 45-60° from the rolling direction. (over)

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Abstract contd.

Decreases in test temperature led to higher strengths and similar anisotropic behavior, with little or no change in ductility. Fracture toughness measurements did not reveal any significant orientation effects, with toughness levels insensitive to the cryogenic temperatures examined. It was not possible to develop valid FCGR data on C(T) samples oriented in either the T-L or T-L plate directions due to out-of-plane cracking. Constant amplitude FCGR data generated on 45° oriented samples are comparable with reference data on similar Weldalite material for the T-L and L-T directions, though a slight degree of anisotropy appears to exist at lower values of ΔK. FCGR data obtained at liquid nitrogen and liquid helium test conditions were identical and only slightly lower than similar data developed under ambient conditions.

FOREWORD

This program was conducted by the University of Dayton Research Institute (UDRI) in cooperation with the Systems Support Division of Wright Laboratory (WL/MLSE) under Air Force Contract Number F33615-90-C-5915 "Quick Reaction Evaluation of Materials & Processes." Mr. Neal Ontko served as contract monitor.

This effort was conducted during the period of August 1991 through June 1993. The authors would like to extend special recognition to Messrs. John Eblin and William Fortener of the University of Dayton who performed all mechanical testing, and to Ms. Mary Ann Phillips of WL/MLSE who provided the test material and ample background information.

This report was submitted by the authors in August 1993.

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SECTION 1
INTRODUCTION

Since their introduction in the early 1980's aluminum-lithium alloys have been purported to be ideal replacements to their conventional, non-lithium containing counterparts in a number of applications due to such mechanical property enhancements as higher specific strength and stiffness. One particular area where aluminum-lithium is expected to outperform conventional aluminum is in cryogenic applications, where their high strength and toughness at low temperatures, coupled with lower density, make them an ideal candidate for liquid fuel storage (i.e., liquid oxygen and hydrogen) for airborne systems. Presently, the leading conventional aluminum alloy for such usages has been 2219, developed in the 1950's primarily as a weldable alloy with high strength and toughness properties at cryogenic conditions and currently used in the main fuel tanks for the Space Shuttle as well as in other similar launch systems.

In the last few years the mechanical behavior and fracture mechanisms at cryogenic temperatures have been reported for many aluminum-lithium alloys such as 2090, 2091, and 8090 [1-8]. One shortcoming of these commercially available alloys, however, which has severely limited their acceptance has been the high degree of anisotropy with respect to mechanical properties. In this effort a more recently developed aluminum-lithium alloy is investigated, Weldalite™, which, as the name implies, was developed specifically for weldability and cryogenic applications[9]. Strength/ductility, fracture toughness, and fatigue crack growth rate properties are developed for plate material at temperatures ranging from room temperature to liquid helium (4K). At each test temperature, the degree of anisotropy with respect to strength and fracture properties is documented. Comparisons are made to the aforementioned 2219 plate alloy.

SECTION 2
MATERIALS AND PROCEDURES

The material examined in this effort was a single plate of Weldalite™ aluminum-lithium, produced and furnished by the Reynolds Metals Co. This particular plate (Lot #901T391A) was delivered in early 1991 as part of the Air Force/Industry Cooperative Test Program on Advanced Aluminum and was originally designated as Weldalite 049 in a RX815-RT70 temper condition. It has since been redesignated as 2095-T8 by the Aluminum Association. In this report the names Weldalite, Weldalite 049 (RX815-RT70), and aluminum 2095-T8 are used interchangeably and refer to this same plate of material. Plate thickness was nominally 12.7 mm (1/2 in). A photomicrograph of the test material is provided in Figure 1. The chemical composition determined for this plate is furnished in Table 1, along with compositional limits established by the Aluminum Association for Al 2095. Lithium content for this particular alloy is lowest among current Al-Li alloys; consequently density reductions are not as great as compared to those of other available Al-Li alloys.

Sub-sized tensile samples were removed from the mid-thickness location of the plate material, oriented in the 0 (L), 30, 45, 60, and 90° (T) directions. Specimen geometry was cylindrical with a 4 mm (0.158 in) test section diameter and 25 mm (1.0 in) gage length (GL). Similar sized tensile samples were likewise removed from a single 6.4 mm (0.25 in) plate of Al 2219-T87 in the 0 (L), 30, 60, and 90° (T) plate directions to serve as a basis for comparison.

For fracture toughness evaluations, C(T) specimens with W = 38 mm (1.50 in) were removed in the 0° (L-T) orientation, as well as the 30, 45, 60, and 90° (T-L) plate directions. Thickness of the toughness samples was limited to the plate thickness. Fatigue crack growth rate (FCGR) data was generated using C(T) specimens with W = 51 mm (2.0 in), and thickness of approximately 6.4 mm (0.25 in). Due to the limited amount of available material, the FCGR samples were removed only from the L-T, T-L, and the 45° plate directions.

Tensile testing was performed in an MTS servo-hydraulic test machine operating in stroke control mode following guidelines established in ASTM E8-90a for Tension Testing of Metallic Materials. A displacement rate of 1.25 mm/min. (0.05 in/min.) was

used for the test temperatures of 21, -73, -196, and -269 °C (70, -100, -321, and -452 °F, respectively). Strain information was obtained using a 25 mm (1.0 inch) GL cryogenic extensometer. Percent elongation was determined using the fit-back method.

Fatigue crack growth and fracture toughness testing was likewise performed in an MTS servo-hydraulic test machine over a similar temperature range. Procedures described in ASTM E647-91 for constant load, K-increasing methods were adhered to. Crack growth data was obtained at all temperatures using a computer-automated data acquisition system developed by the author. Crack length measurements were accomplished using compliance techniques, while growth rates were determined using the secant method as described in the test standard.

Fracture toughness data was obtained at the cryogenic conditions using two standard test methods. For those limited cases where linear elastic behavior was prevalent, K_{Ic} was obtained using the ASTM E399-90 Standard for Plane-Strain Fracture Toughness. For the majority of cases, however, K_{Ic} values were derived from J_{Ic} measurements following those guidelines established in ASTM E813-87. In the latter case, testing was performed using the single specimen J_{Ic} software application program developed by MTS for use with the TestLink™ computer control and data acquisition system. Values of K_{Ic} were converted from the J_{Ic} measurements using the following expression:

$$K_{Ic} = \sqrt{(J_{Ic} \cdot E)}$$

All testing at the -73°C (-100°F) condition was conducted using an environmental chamber which completely enclosed the specimen and extensometer/clip-gage arrangement. Liquid nitrogen was slowly introduced into the chamber through a solenoid valve controlled by a Gulton-West temperature controller. Temperature was maintained to within ±2°C (±4°F) of the desired test temperature. Testing at -196°C (-321°F) was accomplished by submerging the specimen in liquid nitrogen throughout the test.

A liquid helium test chamber, manufactured by Andonion Cryogenics Inc., was used to perform tests at the liquid helium test temperature of 4K (-269°C or -452°F). A special tensile test apparatus, consisting basically of a pull rod within a compression tube, was used to apply load to the specimen while keeping it continually submerged in the

liquid helium. A schematic illustration of the set-up is furnished in Figure 2. The excitation voltage for the extensometer/clip-gage was reduced to approximately 2 VDC to minimize heating of the strain gages which in turn would cause boiling of the liquid helium in the vicinity of the gage and lead to erratic strain readings.

SECTION 3
RESULTS AND DISCUSSION

3.1 TENSILE

Tensile tests results for Weldalite 049 are tabulated in Table 2. For comparative purposes the results of similar testing on Al 2219-T87 6.4 mm (0.25 inch) plate are likewise presented in Table 3. The data shown in each table reflect the results of a single test per condition. Results furnished in Table 2 indicate that the Weldalite material possesses an excellent combination of strength and ductility for the principal plate directions, with strength properties greater than that of all other commercially available Al-Li alloys. Strength data presented for the L and T directions at RT are in good agreement with reference data[11] on identical material; elongation measurements are lower. This may be due to the smaller test section diameter used in this study.

Tensile results for the Weldalite alloy display a high degree of anisotropy for all temperatures investigated, as illustrated in Figure 3 for room temperature and liquid helium test conditions. Strength levels for each temperature are highest for the principal plate directions (L & T) and drop significantly in the 45-60° direction. Ductility inversely follows the strength level at each test temperature, i.e., lowest in the principal directions and highest in the 45-60° direction.

In contrast to this, similar data for 2219 at the same test temperatures are illustrated in Figure 4 and reflect little or no influence of orientation on strength properties. Only at liquid helium conditions does the strength of 2219 show a noticeable drop in the transverse (90°) plate direction relative to the other orientations; for all other temperatures, strength properties are relatively insensitive to orientation. Ductility for 2219 likewise appears insensitive to plate orientation for the cryogenic temperatures examined, though scatter in individual RA and elongation measurements makes subtle differences difficult to resolve.

Regarding the influence of test temperature, both Weldalite and 2219 show a consistent increase in both yield and ultimate strength with decreasing temperature, as illustrated in Figures 5 and 6, respectively, with Weldalite possessing typically a 125 MPa strength advantage over 2219 at any given test condition. Trends of ductility vs. temperature are not as pronounced for either alloy, though a slight increase in % elongation with decreasing temperature for both alloys is noted. The effects of

temperature on strength properties of Weldalite are further illustrated in Figure 7 at the two temperature extremes for the various orientations examined. Yield strength at the liquid helium environment is consistently in excess of 100 MPa over room temperature results for all orientations, while ductility changes little between the two temperatures illustrated. Again, yield strength is lowest and ductility highest in the 45-60° orientation for each temperature extreme.

As a final point regarding tensile strength anisotropy, reference data on similar Weldalite material [8] report short transverse tensile strength values nearly equal to those of the two principal plate directions (L & T) presented herein. Increases in short transverse tensile strength with decreasing temperatures were also reported, not quite to the extent as were developed in this study but still comparable to the in-plane strength levels at all temperatures. Thus, tensile anisotropy which exists in the in-plane dimensions is not apparent in the short dimensions of this material, a notable distinction from other commercial Al-Li alloys.

3.2 FRACTURE TOUGHNESS

Fracture toughness data obtained for the various plate orientations are presented in Table 4 for temperatures ranging from room temperature to 4K (-452°F). The same data is graphically depicted in Figure 8. Results based on a single test specimen per condition indicate no distinct differences in plane strain fracture toughness as a function of orientation for any of the test temperatures examined. Any subtle orientations effects which might exist are masked by the larger variabilty in K_{Ic} measurements. *(Note: the variability in toughness values presented is believed by the authors to be due more as a result of the method in which they were derived from J_{Ic} measurements. An accurate assessment of the J_{Ic} values using the single specimen technique in ASTM 813 is not often exact, particularly with the relative low toughness material/conditions examined herein. Slight errors in compliance crack length values, particularly early in the test, make the location of the material's blunting line subject to approximation and hence may introduces slight errors in J_{Ic} determination. Also, deriving K_{Ic} from $\sqrt{J \cdot E}$ requires an accurate assessment of Young's Modulus; errors in E result in a similar error in K. Hence, errors of 5-10% in the reported K_{Ic} values from J_{Ic} measurements are not unexpected.)* At liquid helium temperature, where K_{Ic} is obtained per ASTM E399 in 3 of the 4 cases, scatter is far less evident. Based on the preceding results, there does not appear to be any pronounced orientation effects on fracture toughness over the cryogenic temperature ranges examined, nor does there appear to be any distinct temperature

dependence on toughness properties. Reference toughness data [8] on similar Weldalite (2095-T851) material developed in the S-L orientation showed a similar insensitivity to cryogenic temperatures, though plane strain toughness levels based on chevron-notch samples were notably lower (see ASTM E 1304 for additional information regarding chevron notch testing).

Comparisons of toughness properties with Al 2219-T87 reference data[11,12] indicate the Weldalite material possesses greater room temperature plane strain toughness (K_{Ic}); however the toughness of 2219-T87 increases significantly with decreasing temperature[8,12], with K_{Ic} values exceeding those of Weldalite at liquid nitrogen temperatures and presumably lower temperatures. Thus, while Weldalite is superior to 2219 under room temperature conditions, the combination of strength and toughness at cryogenic temperatures may not be as advantageous.

3.3 FCGR

Anisotropy effects were documented on the conventional 2219 material at room temperature to serve as a basis for comparison, the results of which are presented in Figure 9. For the conditions listed, there does not appear to be any anisotropy with respect to FCGR properties for this material. For the L-T, T-L, and 45° plate directions, data fall directly on top of each other for the range of ΔK examined. With the Weldalite material in this study, however, it was not possible to develop valid FCGR data on L-T and T-L oriented C(T) samples due to consistent out-of-plane cracking. Side-grooving up to 20% on C(T) samples did not alleviate the angled cracking, as shown in Figure 10 for an L-T oriented sample. For non-side-grooved samples oriented in the 45° direction, however, self-similar cracking did occur as required in ASTM E647. Thus subsequent testing of Weldalite was limited to the 45° plate direction.

The FCGR data developed under ambient conditions on 45° C(T) samples are presented in Figure 11, along with reference data[10] for Weldalite in the L-T and T-L orientations, developed from larger sized C(T) specimens tested under K-controlled (positive K gradient) procedures. Results presented in Figure 11 illustrate a slight increase in growth rates for the 45° direction at the lower values of ΔK; at the moderate to high ΔK levels the data for the three orientations merge. This behavior at the higher stress intensity conditions is consistent with the toughness behavior previously noted which indicated similar fracture toughness values for all plate directions examined. Based on the limited data presented, no distinct orientation effects are noted for

Weldalite with respect to FCGR behavior for the majority of stress intensity ranges examined, though some anisotropy might exist at lower stress conditions. As to an explanation of the out-of-plane cracking noted in this effort, the FCGR testing was performed under constant load, K-increasing conditions beginning at low ΔK levels (i.e., <5 MPa$\sqrt{m}$) where some crack growth anisotropy is noted. Since crack growth resistance is in the 45°direction appears slightly lower than for the principal directions at these lower stress intensities and, given the fact that a high bi-axial stress state near the crack tip exists for the standard C(T) specimen[13], it seems appropriate that cracking might occur more readily in this direction.

The results of cryogenic FCGR testing on Weldalite at RT, liquid nitrogen (77 K), and liquid helium (4K) are furnished in Figure 12. Similar testing on 2219 at RT and liquid nitrogen conditions are likewise furnished in Figure 13. For the conditions listed in the figures, the Weldalite material shows only a slight decrease in growth rates for the two cryogenic conditions as compared to data developed at RT. Data obtained at liquid helium and liquid nitrogen are identical for the range of ΔK examined and converge with the RT data at the higher ΔK values. A similar trend is noted for the 2219 alloy. Though not presented in the same figure, the FCGR data obtained for Weldalite and 2219 are nearly identical over the range of ΔK examined.

SECTION 4
CONCLUSIONS

In this effort the tensile strength, fracture toughness, and fatigue crack growth rate data for a single plate of Weldalite 049 (Al 2095-T8) were developed and examined for anisotropy with respect to mechanical properties over a range of cryogenic temperatures. Based on test results obtained from a single plate of material, the following conclusions are rendered:

1. In-plane tensile strength/ductility anisotropy for the Weldalite material is pronounced at temperatures ranging from RT to liquid helium (4K) conditions. Tensile and yield strength are greatest in the principal plate directions (L & T), lowest in the 45-60° direction. Ductility is inversely related to strength in all orientations: lowest in the principal directions and highest in 45-60° direction.

2. Tensile and yield strength increase dramatically with decreasing temperature for all plate directions examined. Ductility, however, is relatively unaffected over the cryogenic temperature range investigated.

3. Strength levels of Weldalite are consistently superior to the conventional aluminum alloy 2219 at all temperatures, with no compromise in ductility over the range of temperatures examined.

4. There is no distinct influence of in-plane orientation on fracture toughness of Weldalite 049 at any of the temperatures examined. Plane strain fracture toughness (K_{Ic}) is relatively insensitive to cryogenic temperatures ranging from RT to liquid helium.

5. No significant influence of orientation on FCGR properties is noted for the majority of stress intensities examined, although at low ΔK levels a sight increase in growth rates was noted for the 45° plate direction. Data obtained on Weldalite C(T) samples oriented in the 45° direction were similar to data obtained on Al 2219-T87 plate material. The influence of the lower test temperatures on the Weldalite material led to a slight reduction in growth rates, more evident at lower values of ΔK than for higher ΔK conditions.

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Table 1.
Chemical Composition of Weldalite 049 (Al 2095-T8) Test Plate
(wt. %)

Lithium	Copper	Magnesium	Silver	Zirconium	Iron	Silicon	Titanium
1.30	4.17	0.34	0.33	0.126	0.057	0.038	0.028

Compositional Limits for 2095 (from Aluminum Association)*
(wt. %)

Lithium	Copper	Magnesium	Silver	Zirconium	Iron	Silicon	Titanium
0.7-1.5	3.9-4.6	0.25-0.8	0.25-0.6	0.04-0.18	0.15	0.12	0.10

* - values given represent maximum unless range given.

TABLE 2

TENSILE DATA SUMMARY FOR WELDALITE 049 (Al 2095-T8) PLATE

TEST TEMP. °C	TEST TEMP. (°F)	ORIENT. (°)	YS MPa	YS (KSI)	UTS MPa	UTS (KSI)	ELONG. %	R.A. %	E GPa	E (MSI)	n**
21	70	0	573	83.1	617	89.4	7.4	27.0	73	10.6	0.080
		30	526	76.3	580	84.2	8.8	29.2	71	10.3	0.069
		45	476	69.0	520	75.5	8.9	41.7	68	9.9	0.058
		60	463	67.2	527	76.4	8.3	43.8	69	10.1	0.055
		90	568	82.4	613	88.9	8.8	30.6	75	10.9	0.073
-73	-100	0	595	86.2	637	92.3	8.8	26.5	78	11.3	0.076
		30	534	77.4	595	86.3	8.9	30.6	75	10.8	0.067
		45	493	71.5	543	78.7	11.4	21.6	76	11.0	0.065
		60	499	72.4	567	82.2	10.1	42.3	78	11.3	-
		90	586	85.0	633	91.9	8.0	26.2	79	11.5	0.069
-196	-321	0	672	97.5	746	108.2	*	22.4	83	12.0	0.089
		30	598	86.7	695	100.8	10.7	33.8	71	10.2	0.088
		45	549	79.7	618	89.6	15.2	46.4	59	8.5	0.083
		60	549	79.7	631	91.5	10.7	43.8	80	11.6	0.066
		90	647	93.8	720	104.4	9.6	26.0	80	11.7	0.091
-269	-452	0	712	103.3	855	124.1	11.3	29.3	82	11.9	0.117
		30	668	97.0	828	120.1	12.7	23.4	80	11.6	0.111
		45	610	88.4	725	105.1	16.8	33.0	70	10.2	0.095
		60	603	87.4	717	104.0	12.8	45.3	80	11.6	0.087
		90	709	102.8	852	123.6	11.4	27.7	79	11.5	0.108

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* - broke outside G.L.

** - strain hardening exponent

TABLE 3

TENSILE DATA SUMMARY FOR
Al 2219-T87 PLATE

TEST TEMP. °C	TEST TEMP. (°F)	ORIENT. (°)	YS MPa	YS (KSI)	UTS MPa	UTS (KSI)	ELONG. %	R.A. %	E GPa	E (MSI)
21	70	0	391	56.7	479	69.5	8.1	28.5	73	10.6
		30	378	54.8	463	67.2	7.8	32.0	72	10.4
		60	387	56.2	472	68.4	7.6	25.1	75	10.9
		90	386	56.0	470	68.1	7.0	22.6	77	11.2
-73	-100	0	458	66.4	512	74.3	7.9	30.8	82	11.9
		30	400	58.0	494	71.7	8.1	27.8	80	11.6
		60	409	59.3	502	72.9	7.2	26.8	77	11.2
		90	408	59.2	499	72.4	7.1	23.1	79	11.4
-196	-321	0	463	67.1	591	85.7	9.0	30.1	80	11.7
		30	447	64.8	573	83.2	8.9	27.6	75	10.9
		60	457	66.3	580	84.1	8.2	27.6	77	11.2
		90	462	67.0	588	85.3	7.7	22.9	87	12.6
-269	-452	0	503	73.0	718	104.1	10.4	28.6	87	12.6
		30	487	70.7	689	99.9	10.8	26.2	77	11.1
		60	506	73.4	711	103.1	10.5	23.6	83	12.0
		90 [1]	429	62.2	597	86.7	9.6	25.9	61	8.8

UDRI

[1] - Broke in threads after YS was determined; re-tested to failure.

TABLE 4

FRACTURE TOUGHNESS SUMMARY FOR WELDALITE 049 (Al 2095-T8) PLATE

TEST TEMP. °C	(°F)	ORIENT.	K_{Ic} [1] MPa$\sqrt{m}$	(KSI$\sqrt{in}$)
21	70	0	35.8	32.6
		30	37.7	34.3
		45	33.5	30.5
		60	35.4	32.3
		90	35.3	32.1
-73	-100	0	35.8	32.6
		30	34.0	31.0
		45	36.8	33.5
		60	38.2	34.8
		90	38.4	34.9
-196	-321	0	35.1	31.9
		30	35.0	31.8
		45	32.6	29.7
		60	27.4	24.9
		90	31.6	28.8
-269	-452	0	34.3	31.2
		30	-	-
		45	36.4 [2]	33.1
		60	37.0 [2]	33.7
		90	34.8 [2]	31.7

UDRI

[1] - K_{Ic} derived from J_{Ic} data ($K = \sqrt{J^*E}$) except where noted.
[2] - K_{Ic} developed per ASTM E399.

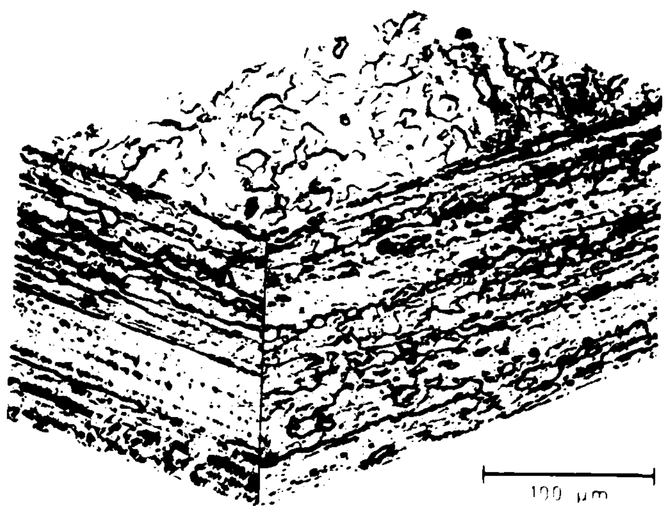
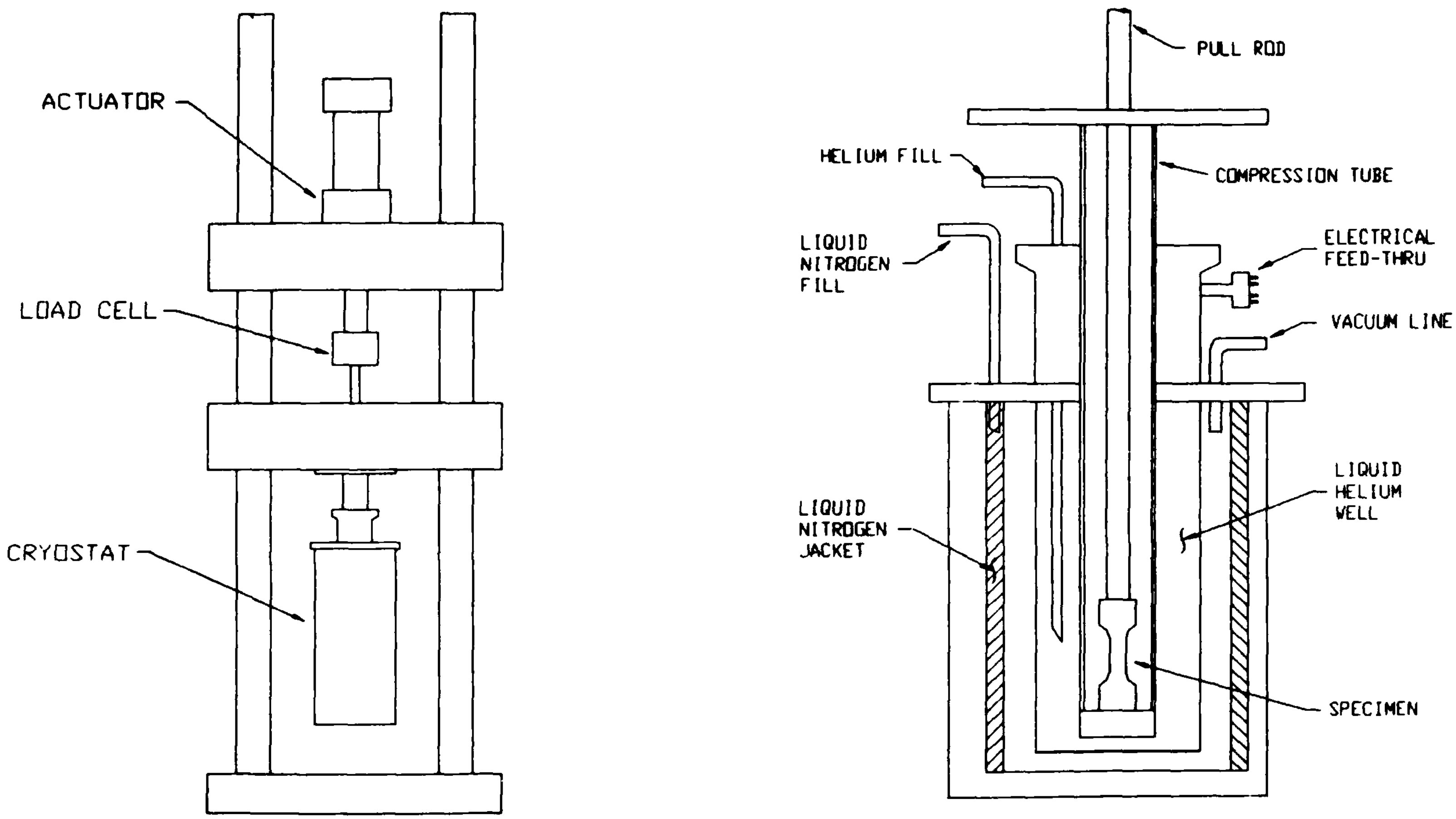


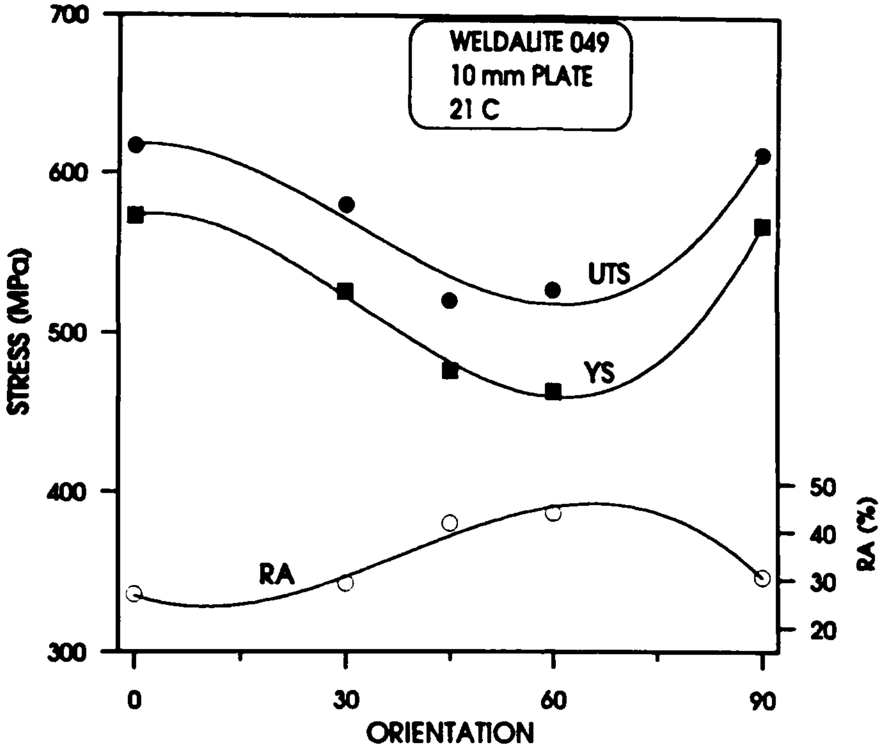
Figure 1. Photomicrograph of Weldalite™ 049 Test Plate.



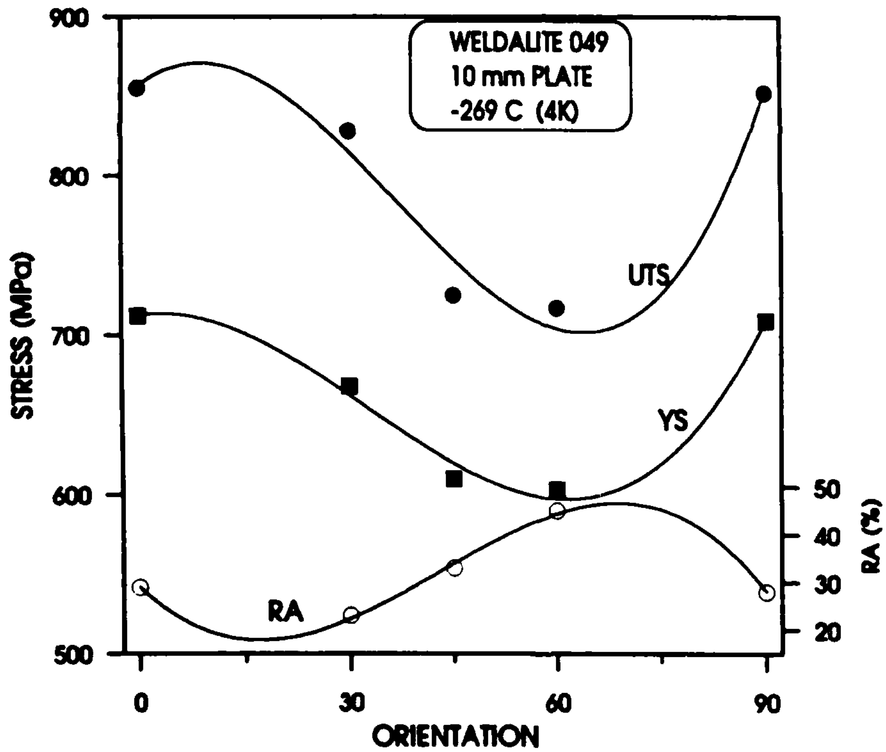
(a) Liquid Helium Test Chamber Installed in Test Frame

(b) Liquid Helium Test Chamber

Figure 2. Setup for Liquid Helium Tests.

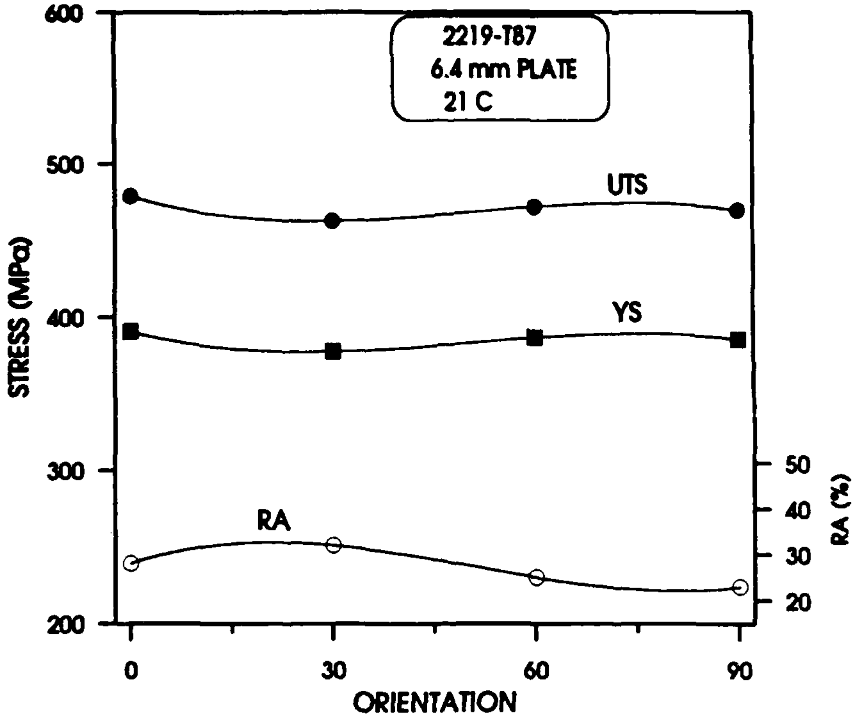


(a) Room Temperature

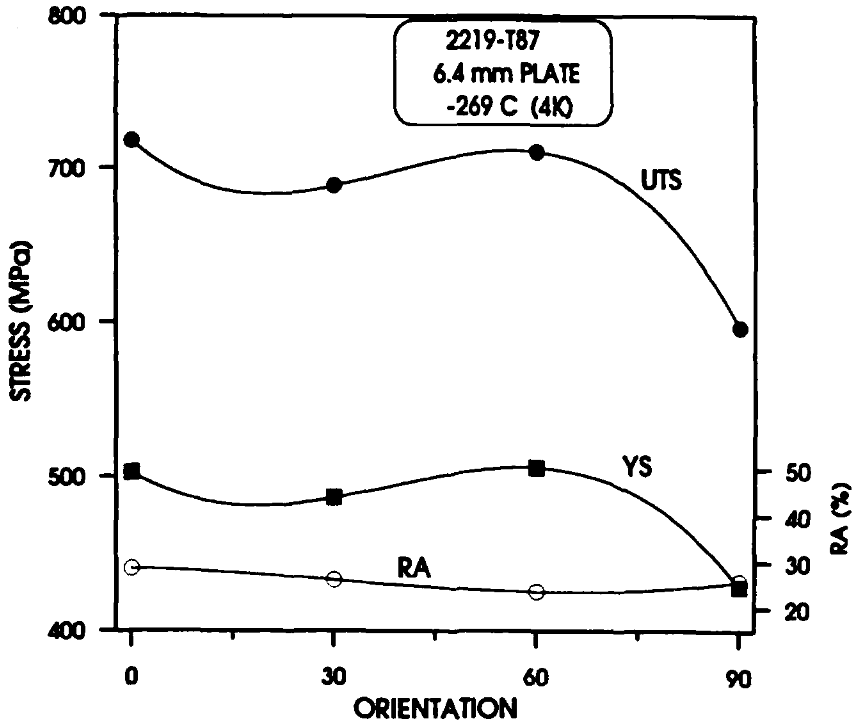


(b\ Liquid Helium

Figure 3. Tensile Properties vs. Orientation for Weldalite 049 at (a) Room Temperature and (b) Liquid Helium Conditions.

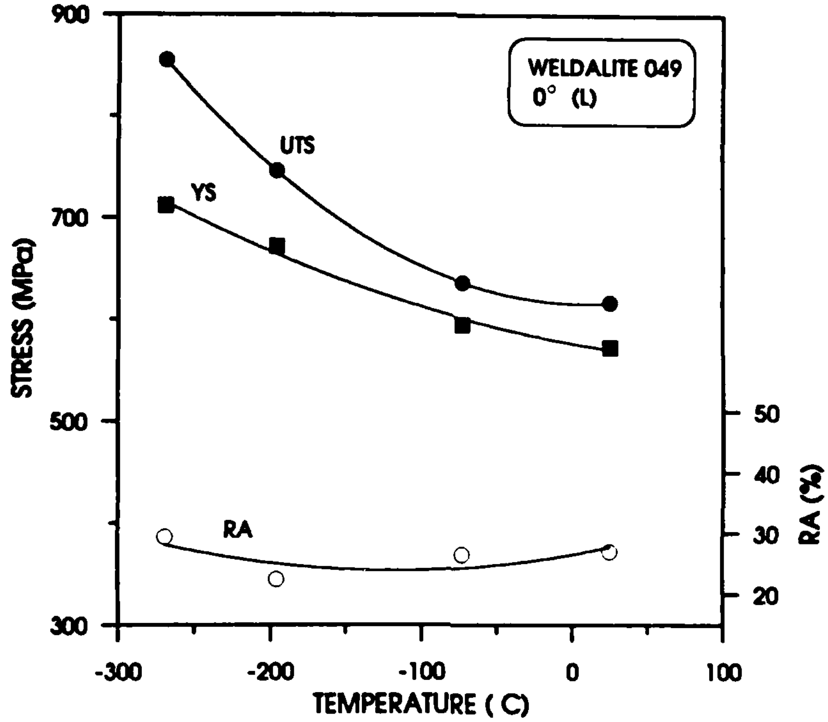


(a) Room Temperature

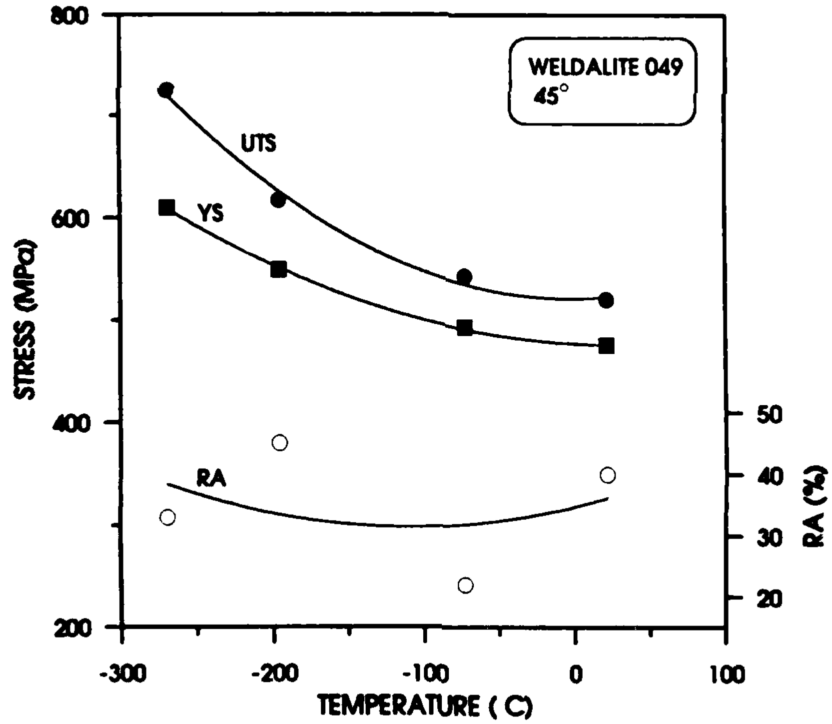


(b) Liquid Helium

Figure 4. Tensile Properties vs Orientation for Al-2219 Plate at (a) RT, and (b) Liquid Helium.

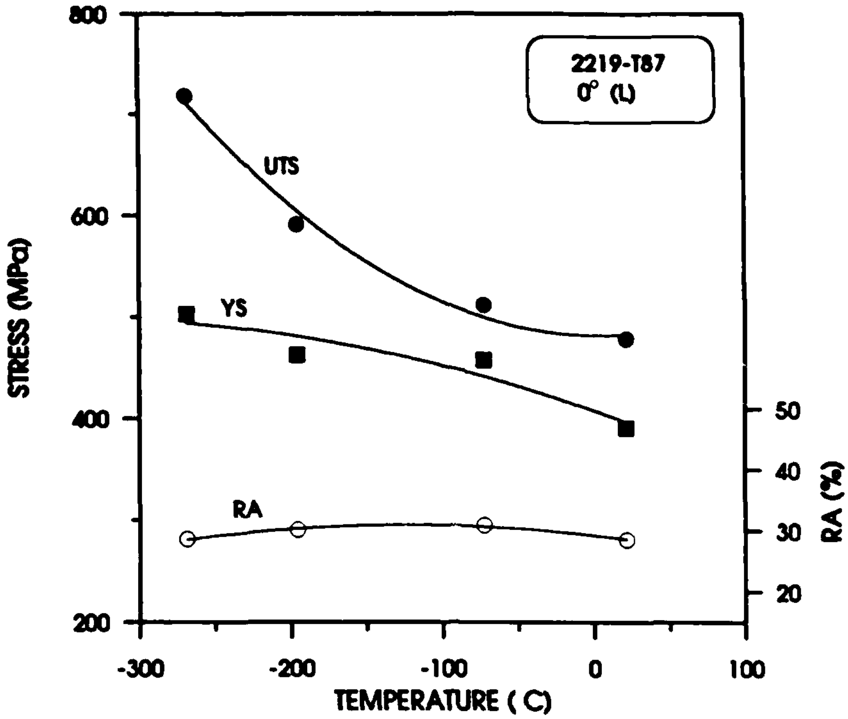


(a) Longitudinal

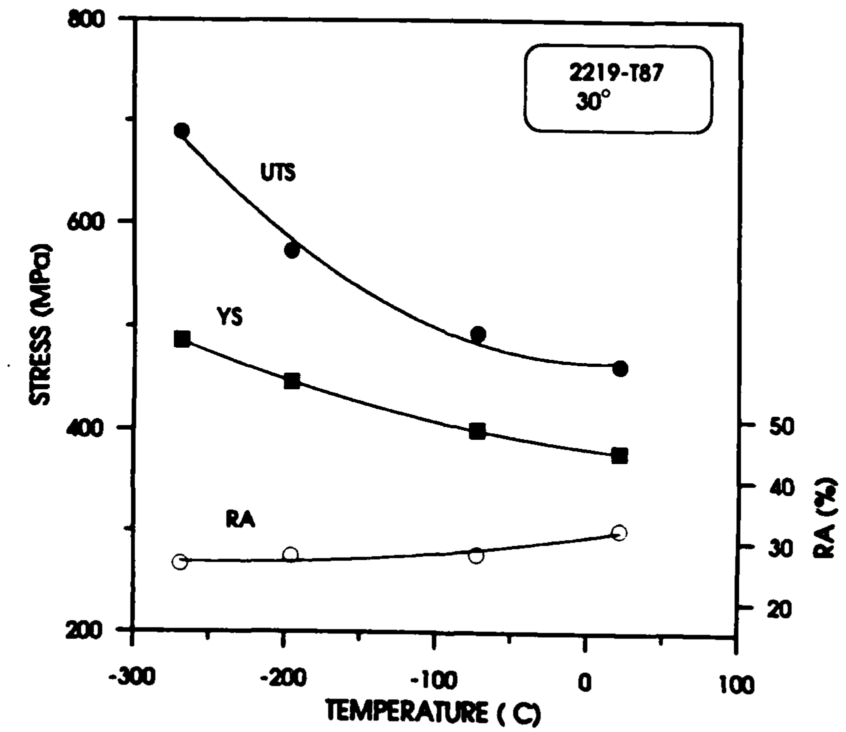


(b) 45° to Rolling Direction

Figure 5. Strength vs Temperature for Weldalite 049 for (a) L Orientation, and (b) 45° Orientation.



(a) Longitudinal



(b) 30° to Rolling Direction

Figure 6. Strength vs Temperature for Al 2219-T87 for (a) L Orientation, and (b) 30° Orientation.

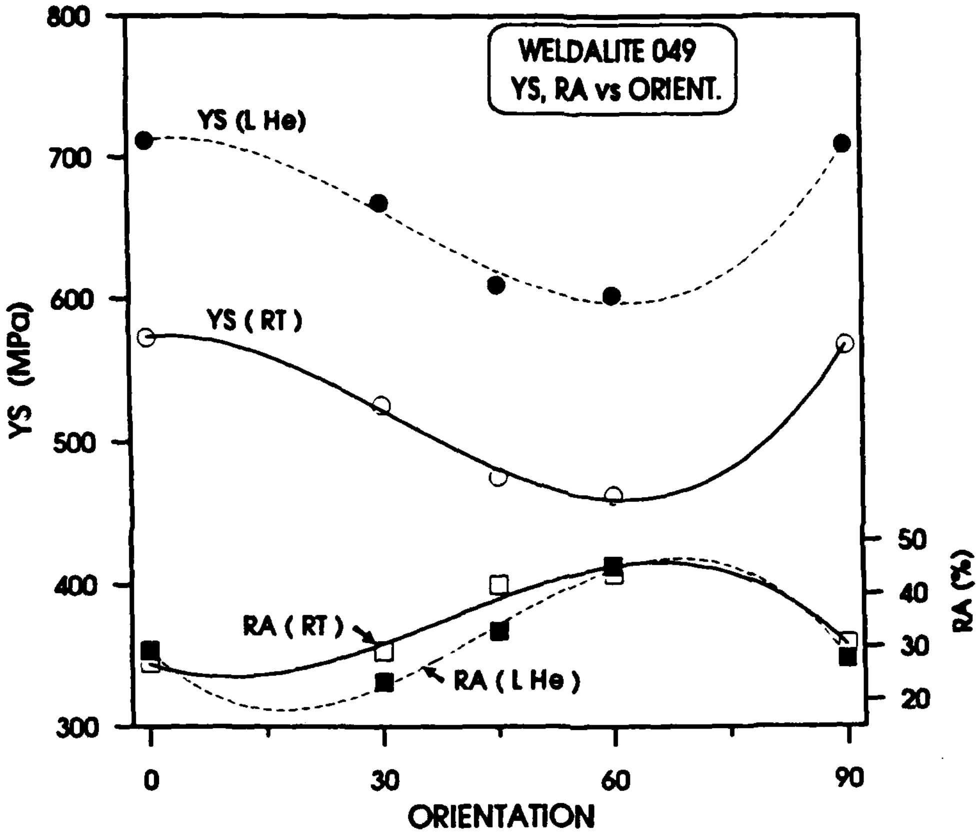


Figure 7. Room Temperature and Liquid Helium YS/Ductility vs Orientation for Weldalite 049.

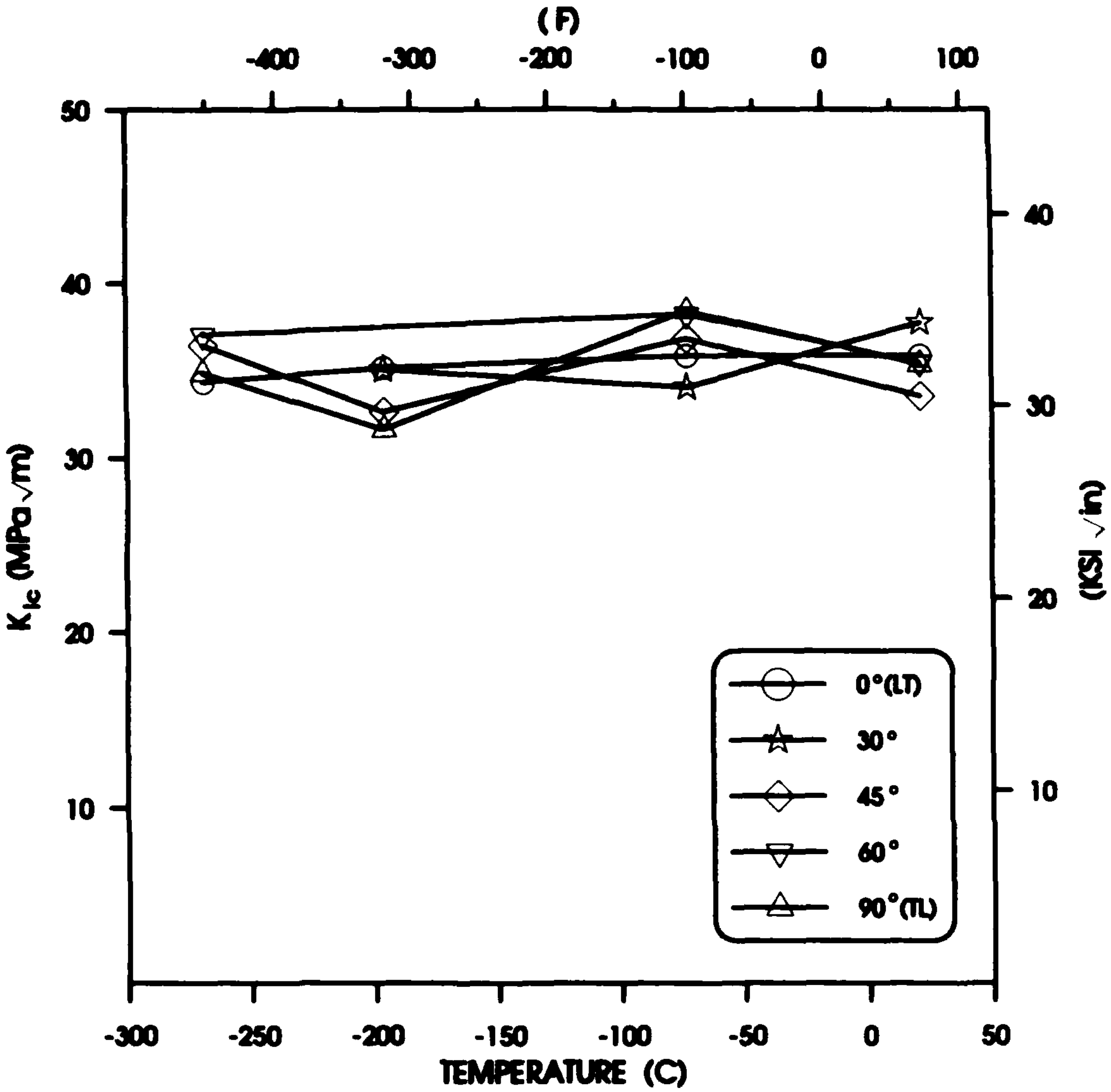


Figure 8. Fracture Toughness vs Temperature for Weldalite 049 at Various Orientations.

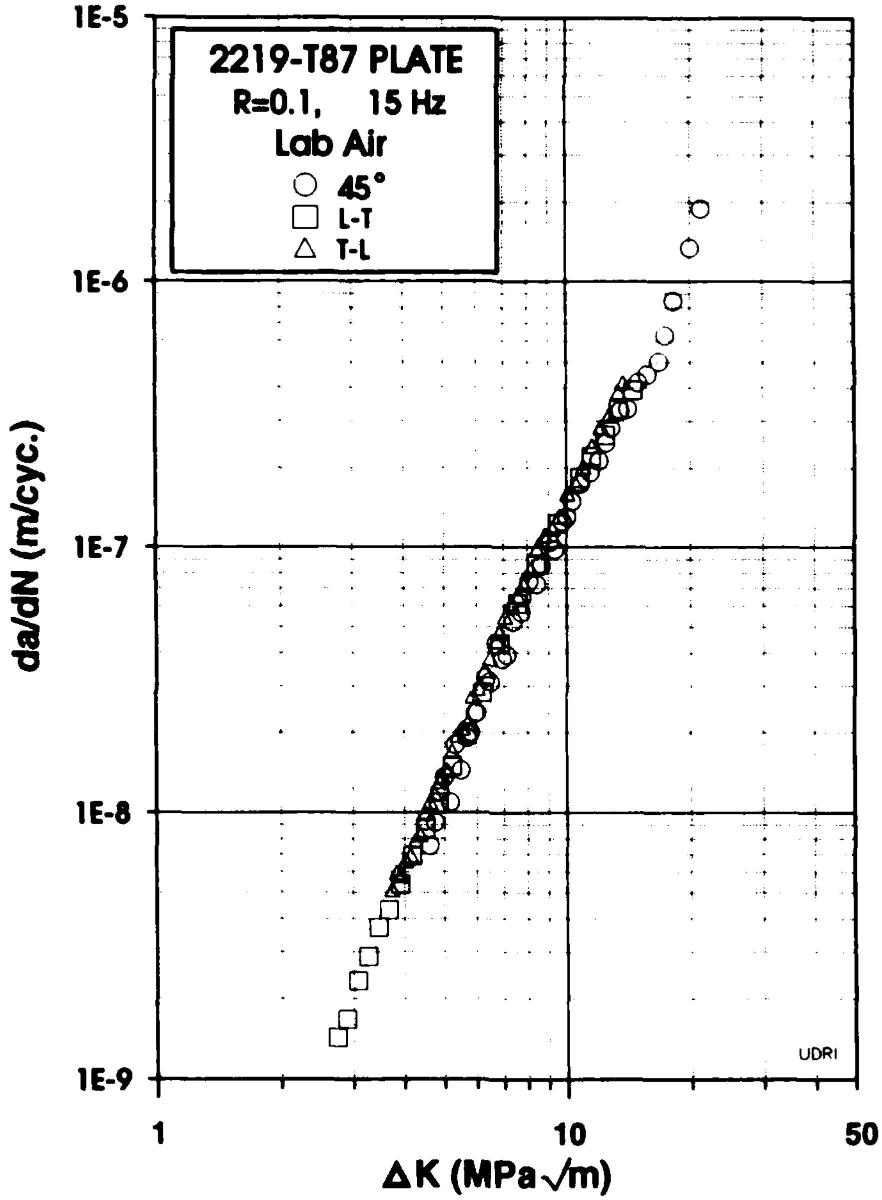


Figure 9. Room Temperature FCGR Results for Al 2219-T87 at Various Orientations.

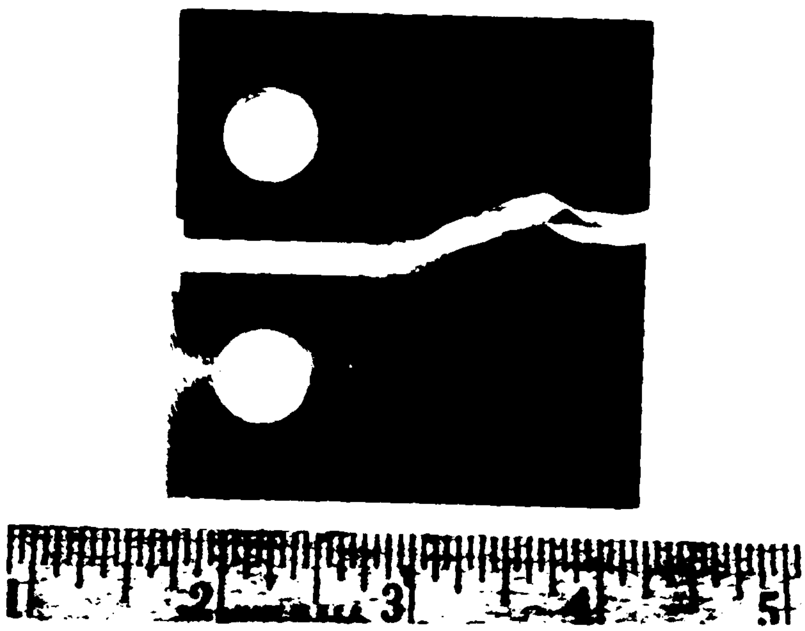


Figure 10. Photograph of L-T Weldalite 049 Crack Growth Sample with 20% Side-Groove.

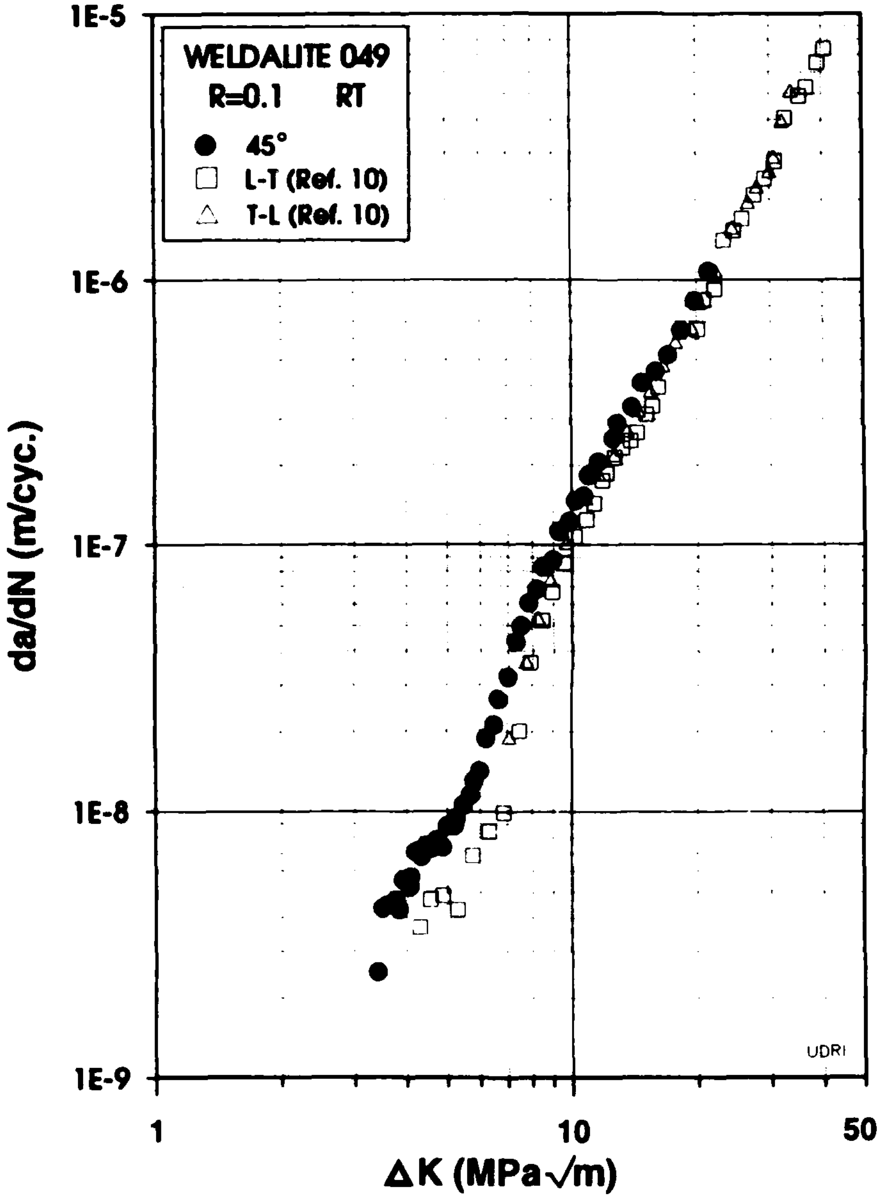


Figure 11. Room Temperature FCGR Data for Weldalite 049 at Various Orientations.

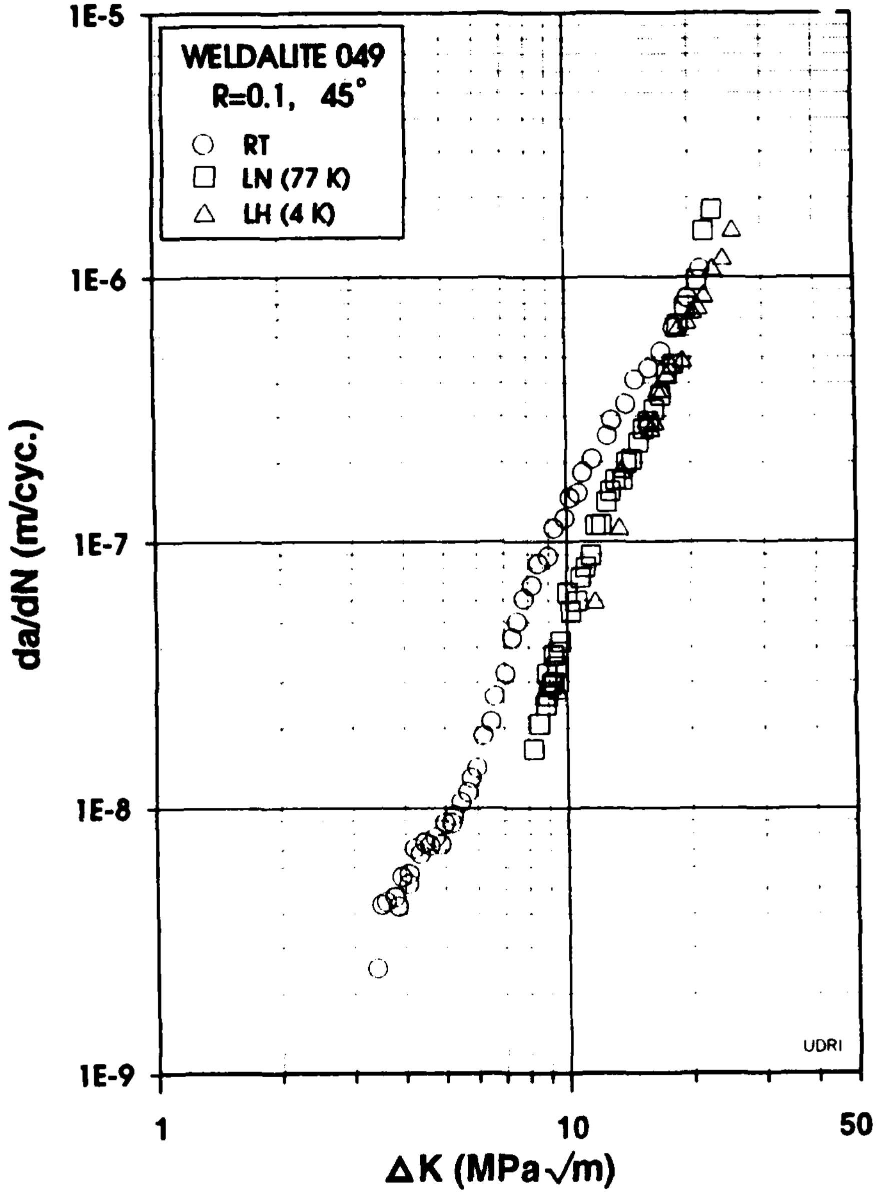


Figure 12. FCGR Data for Weldalite 049 at Cryogenic Temperatures.

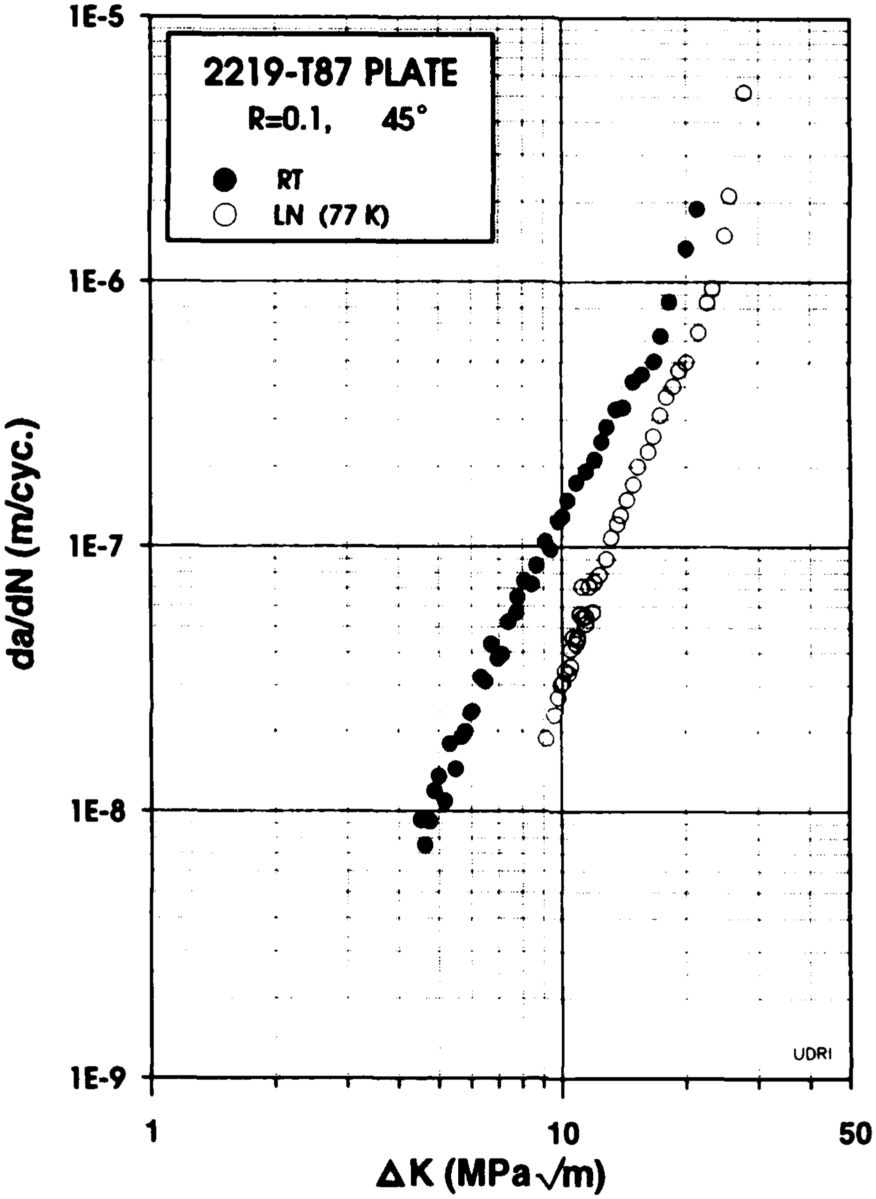


Figure 13. FCGR Data for AL 2219 at Room and Liquid Nitrogen Conditions.

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